

A *Spitzer*-IRS view of early-type galaxies with cuspy/core nuclei and with fast/slow rotation (Research Note)

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Received; accepted

ABSTRACT

Context. The recent literature suggests that an evolutionary dichotomy exists for early-type galaxies (Es and S0s, ETGs) whereby their central photometric structure (*cuspy* versus *core* central luminosity profiles), and figure of rotation (fast (FR) vs. slow (SR) rotators), are determined by whether they formed by “wet” or “dry” mergers.

Aims. We consider whether the mid infrared (MIR) properties of ETGs, with their sensitivity to accretion processes in particular in the last few Gyr (on average $z \lesssim 0.2$), can put further constraints on this picture.

Methods. We investigate a sample of 49 ETGs for which nuclear MIR properties and detailed photometrical and kinematical classifications are available from the recent literature.

Results. In the stellar light *cuspy/core* ETGs show a dichotomy that is mainly driven by their luminosity. However in the MIR, the brightest *core* ETGs show evidence that accretions have triggered both AGN and star formation activity in the recent past, challenging a “dry” merger scenario. In contrast, we do find, in the Virgo and Fornax clusters, that *cuspy* ETGs, fainter than $M_{K_s} = -24$, are predominantly passively evolving in the same epoch, while, in low density environments, they tend to be more active.

A significant and statistically similar fraction of both FR ($38^{+18}_{-11}\%$) and SR ($50^{+34}_{-21}\%$) shows PAH features in their MIR spectra. Ionized and molecular gas are also frequently detected. Recent star formation episodes are then a common phenomenon in both kinematical classes, even in those dominated by AGN activity, suggesting a similar evolutionary path in the last few Gyr.

Conclusions. MIR spectra suggest that the photometric segregation between *cuspy* and *core* nuclei and the dynamical segregation between FR and SR must have originated before $z \sim 0.2$.

Key words. Galaxies: elliptical and lenticular, cD – Infrared: galaxies – Galaxies: fundamental parameters – Galaxies: formation – Galaxies: evolution

1. Introduction

A relatively large fraction of ETGs at high-redshift show clear evidence of interaction and/or merger morphologies and active star formation (e.g. Treu et al. 2005) supporting the model view these galaxies are produced by a halo merger process (see e.g. Mihos 2004; Cox et al. 2008; Khochfar et al. 2011; De Lucia et al. 2011, and reference therein). A further element for high-redshift formation scenarios comes from their measured $[\alpha/\text{Fe}]$ ratios, encoding information about the time-scale of star formation. In massive ETGs this ratio has super-solar values, suggesting that they formed on relatively short time-scales (see e.g. Chiosi et al. 1998; Granato et al. 2004; Thomas et al. 2005; Annibali et al. 2007; Clemens et al. 2009). Annibali et al. (2007) estimated that a fair upper limit to the recent *rejuvenation* episodes is $\sim 25\%$ of the total galaxy mass but that they are typically much less intense than that (see e.g. the *Spitzer*-IRS study of NGC 4435 by Panuzzo et al. 2007). However, rejuvenation signatures in ETGs are often detected, not only in the galaxy nucleus, but also in the disk, rings and even in galaxy outskirts, as clearly shown by GALEX (e.g. Rampazzo et al. 2007; Marino et al. 2009; Salim & Rich 2010;

Thilker et al. 2010; Marino et al. 2011), so that the different phases of galaxy assembly/evolution, and their link to morphological and kinematical signatures, are vivaciously debated.

The merger process may involve either relatively few (major) or multiple (minor) events during the galaxy assembly. Furthermore, it may or may not include dissipation (and star formation), two possibilities often called “wet” and “dry” mergers, respectively (see e.g. van Dokkum 2005). Other mechanisms, however, like conversion of late-type galaxies into ETGs by environmental effects, like strangulation, ram-pressure etc. (e.g. Boselli & Gavazzi 2006), and by energy feedback from supernovae may also be important (e.g. Kormendy et al. 2009).

Two *observable* quantities are thought to distinguish ETGs produced by “wet” and “dry” mergers. The first, mainly fruit of high resolution observations with the *Hubble* Space Telescope and of high precision photometric analyses, is the presence of either a *cusp* or a *core* in the inner galaxy luminosity profile (Lauer et al. 1991, 1992; Côté et al. 2006; Turner et al. 2012). In contrast to *cuspy* profiles, the surface brightness in *core* profiles becomes shallower as $r \rightarrow 0$. The same concept is considered by Kormendy et al. (2009) who divide ETGs into *cuspy-core* and *core-less*, depending on whether the luminos-

ity profile *misses light* or has an *extra-light* component with respect to the extrapolation of the Sersic’s law at small radii. Kormendy et al. (2009) suggest that *cuspy-core* nuclei have been scoured by binary black holes (BHs) during (the last) dissipationless, “dry”, major merger. In contrast, *core-less* nuclei originate from “wet” mergers. Analogously, Côté et al. (2006) and Turner et al. (2012) found an extra stellar nucleus in the profile decomposition of ETGs in their Virgo (ACSVCS) and Fornax (ACSFCS) surveys in addition to simple Sersic profiles, in particular in low-luminosity/(mass) ETGs. They proposed that the most important mechanism for the assembly of a stellar nucleus is the infall of star clusters through dynamical friction, while for more luminous/(massive) galaxies a “wet scenario” (gas accretion by mergers/accretions and tidal torques) dominates.

The second observable quantity is the kinematical class. The class is defined by a parameter describing the specific baryonic angular momentum defined as follows, $\lambda_r = \langle r|V| \rangle / \langle r \sqrt{V^2 + \sigma^2} \rangle$, where r is the galacto-centric distance, V and σ are luminosity weighted averages of the rotation velocity and velocity dispersion over a two-dimensional kinematical field. The measure refers to the inner part of the galaxy, typically of the order or less than 1 effective radius, r_e , i.e. significantly larger than the regions where cusps and cores are detected. λ_r divides ETGs into the two classes of fast (FR) and slow (SR) rotators (Emsellem et al. 2011, and reference therein). FR are by far the majority of ETGs ($86 \pm 2\%$ in the ATLAS^{3D} survey). SR represent massive ETGs that might have suffered from significant merging without being able to rebuild a fast rotating component. Khochfar et al. (2011) find that the underlying physical reason for the different growth histories is the slowing down, and ultimately complete shut-down, of gas cooling in massive, SR galaxies. On average, the last gas-rich major merger interaction in SR happens at $z > 1.5$, followed by a series of minor mergers which build-up the outer layers of the remnant, i.e. do not feed the inner part of the galaxy.

FRs in the models of Khochfar et al. (2011) have different formation paths. The majority (78%) have bulge-to-total stellar mass ratios (B/T) larger than 0.5 and manage to grow stellar discs due to continued gas cooling as a results of frequent minor mergers. The remaining 22% live in high-density environments and consist of low B/T galaxies with gas fractions below 15%, that have exhausted their cold gas reservoir and have no hot halo from which gas can cool. Summarizing, a dissipative merging and/or a gas accretion episode from interacting companions, could be the way for the galaxy to rebuild a fast-rotating disk-like component. SR and FR basically correspond to the paradigms of “dry” vs. “wet” accretions/mergers respectively.

Recently, Lauer (2012) attempted to unite the structural and kinematical views, claiming that they are the two aspects of the same process. Using the specific angular momentum $\lambda_{r_e/2}$, computed from the 2D kinematics within half the effective radius by Emsellem et al. (2011), Lauer (2012) showed that *core* galaxies have rotation amplitudes $\lambda_{r_e/2} \leq 0.25$ while all galaxies with $\lambda_{r_e/2} > 0.25$ and ellipticity $\epsilon_{r_e/2} > 0.2$ lack cores. Some FR have a core profile but they argue that both figure of rotation and the central structure of ETGs should be used together to separate systems that appear to have formed from “wet” and “dry” mergers. Krajnović et al. (2013b) show, however, that there is a genuine population of FR with cores. They suggest that the cores of both FR and SR are made of old stars and are found in galaxies typically lacking molecular and atomic gas, with few exceptions.

For the sake of simplicity throughout the paper, we will call *core* ETGs those galaxies for which the luminosity profile shall

low out as $r \rightarrow 0$ (i.e. cuspy-core in Kormendy et al. (2009), core in Lauer (2012), non-nucleated in Côté et al. (2006); Turner et al. (2012)). We will refer to *cuspy* ETGs as those which present an extra central luminosity component (i.e. core-less in Kormendy et al. (2009), power-law + intermediate in Lauer (2012), nucleated in Côté et al. (2006); Turner et al. (2012)) with respect to a fit of a Sersic model. Depending on the accurate surface brightness profile decomposition performed by the above authors, rarely the *cuspy* versus *core* classification given by different authors for the same ETG is discrepant.

This note aims to contribute to the debate on the origin of *core/cuspy* and FR/SR ETGs, and the connection to the “wet” vs. “dry” merger hypotheses, using mid-infrared (MIR) spectra of well-studied ETGs. The paper is organized as follows. In § 2 we briefly describe how *Spitzer*-IRS spectra trace the recent few Gyr evolution in ETGs. We present the MIR vs. the *cuspy/core* nuclear properties of ETGs (Kormendy et al. 2009; Côté et al. 2006; Turner et al. 2012; Lauer 2012) in § 3, and vs. the FR/SR kinematical classes (Emsellem et al. 2011) in § 4. Conclusions are presented in § 5.

2. A classification of *Spitzer*-IRS spectra of ETGs

Using *Spitzer*-IRS, Rampazzo et al. (2013) have recently produced an atlas of low resolution MIR spectra, of 91 nearby ($D \leq 72$ Mpc) ETGs in the *Revised Shapley-Ames Catalog* (RSA). Spectra are extracted within a common aperture ($3.6'' \times 18''$) providing an integral view of the galaxy’s inner region. On average, the area covered by the rectangular IRS aperture is about 2-3 times the area of a circle of radius $r_e/8$. MIR spectra then cover a region where the *cuspy/core* profiles and/or the departures from the Sersic’s profile are measured, as well as a significant part of the region where FR vs. SR are separated, using e.g. $\lambda_{r_e/2}$. In addition, “dry” vs. “wet” mergers *maximize* their possible signatures in the galaxy nucleus, as shown by the study of line-strength indices (e.g. Annibali et al. 2007, and references therein), by counter-rotating components (e.g. Emsellem et al. 2011) and morphological peculiarities such as irregular/chaotic dust-lanes (e.g. Côté et al. 2006; Turner et al. 2012).

For each galaxy, the atlas provides the fully reduced and calibrated spectrum, the intensity of nebular and molecular emission lines and Polycyclic Aromatic Hydrocarbons (PAHs), after a template spectrum of a passively evolving ETG has been subtracted. Spectra are classified into five mid-infrared classes, ranging from AGN (class-4) and star forming nuclei (class-3), transition class-2 (with PAHs) and class-1 (no-PAHs) to passively evolving nuclei (class-0) (Bressan et al. 2006). Panuzzo et al. (2011) suggest that each of the five MIR classes is a snapshot of the evolution of ETG nuclei during an accretion episode, starting from, and ending with, a class-0 spectrum (see their Figure 11). Vega et al. (2010) suggest that anomalous PAHs in class-2 spectra are produced by carbon stars which are present in stellar populations with ages in the range of a few Gyr (Nanni et al. 2013, see their Table 1), depending on the metallicity, corresponding, on average, to a redshift coverage $z \lesssim 0.2$.

MIR spectral classes show a dichotomy between the Es and S0s. i.e. the classical morphological classification provided by RSA. Rampazzo et al. (2013) found that $46^{+11}_{-10}\%$ of Es and $20^{+11}_{-7}\%$ of S0s have a spectrum of class-0, i.e. Es are significantly more passive than S0s. A small, similar ($\sim 9^{+4}_{-3}\%$) fraction of Es and S0s have PAH ratios typical of star forming galaxies. PAHs are detected in $47^{+8}_{-7}\%$ of ETGs and with a statistically similar fraction in Es and S0s. Basically half of ETGs ($41^{+8}_{-7}\%$)

Table 1. The Virgo sample in Kormendy et al. (2009) with *Spitzer*-IRS MIR class

Galaxy	RSA Type	n_{tot}	% light	M_{K_s}	MIR class	Kinematical class	Kinematical and Morphological peculiarities	Dust
core			missing light					
NGC 4472	E1/S0 ₁ (1)	$5.99^{+0.31}_{-0.29}$	-0.50 ± 0.05	-25.73	1	SR	CR s-s (1)	Y
NGC 4486	E0	$11.84^{+1.79}_{-1.19}$	-4.20 ± 1.00	-25.31	4	SR	SC(2), jet	Y
NGC 4649	S0 ₁ (2)	$5.36^{+0.38}_{-0.32}$	-1.05 ± 0.07	-25.35	1	FR	asym. rot. curve (6)	N
NGC 4365	E3	$7.11^{+0.40}_{-0.35}$	-0.63 ± 0.07	-25.19	0	SR	Faint SW fan (4)	N
NGC 4374	E1	$7.98^{+0.71}_{-0.56}$	-1.52 ± 0.05	-25.13	2	SR	$V \approx 0$ (3); SC (2)	Y
NGC 4261	E3	$7.49^{+0.82}_{-0.60}$	-1.84 ± 0.05	-25.24	4	SR	NW tidal arm, faint SE fan (4)	Y
NGC 4382	S0 ₁ (3) pec	$6.12^{+0.31}_{-0.27}$	-0.18 ± 0.06	-25.13	1	FR	MC(2), shells (7)	Y
NGC 4636	E0/S0 ₁ (6)	$5.65^{+0.48}_{-0.28}$	-0.22 ± 0.04	-24.42	2	SR	gas irr. motion (a)	Y
NGC 4552	S0 ₁ (0)	$9.22^{+1.13}_{-0.83}$	-1.23 ± 0.09	-24.31	2	SR	KDC (2) shells (4)	Y
cuspy			extra light					
NGC 4621	E5	$5.36^{+0.30}_{-0.28}$	0.27 ± 0.06	-24.13	0	FR	KDC (2)	N
NGC 4473	E5	$4.00^{+0.18}_{-0.16}$	8.80 ± 1.00	-23.77	0	FR	MC (2)	N
NGC 4478	E2	$2.07^{+0.08}_{-0.07}$	1.12 ± 0.15	-23.15	0	FR	...	N
NGC 4570	S0 ₁ (7)/E7	3.69 ± 0.50	...	-23.49	0	FR	MC (2)	N
NGC 4660	E5	4.43 ± 0.38	...	-22.69	0	FR	MC (2)	N
NGC 4564	E6	4.69 ± 0.20	...	-23.09	0	FR	SC (2)	N

Notes: *Core* and *cuspy* galaxies correspond to cuspy-core and core-less, respectively, in Kormendy et al. (2009). The Sersic's index, n_{tot} , and the percentage of extra light are taken from Kormendy et al. (2009). The M_{K_s} absolute magnitude and the MIR class is obtained from Brown et al. (2011) and Rampazzo et al. (2013). Kinematical classes are from Emsellem et al. (2011). Kinematical and morphological peculiarities are coded as follows: CR s-s: counter rotation stars vs. stars (1) Corsini et al. (1998); KDC indicates a kinematically decoupled component, not necessarily counter-rotation; MC multiple components; SC single component Krajnović et al. (2008) (2). A description of the kinematic and morphological peculiarities of the galaxies and full references are reported in: (3) Emsellem et al. (2004); (4) Tal et al. (2009); (5) Malin & Carter (1983); (6) Pinkney et al. (2003); (7) Kormendy et al. (2009). Dust properties (Y if present) are taken from Côté et al. (2006) and Table B3 in Rampazzo et al. (2013).

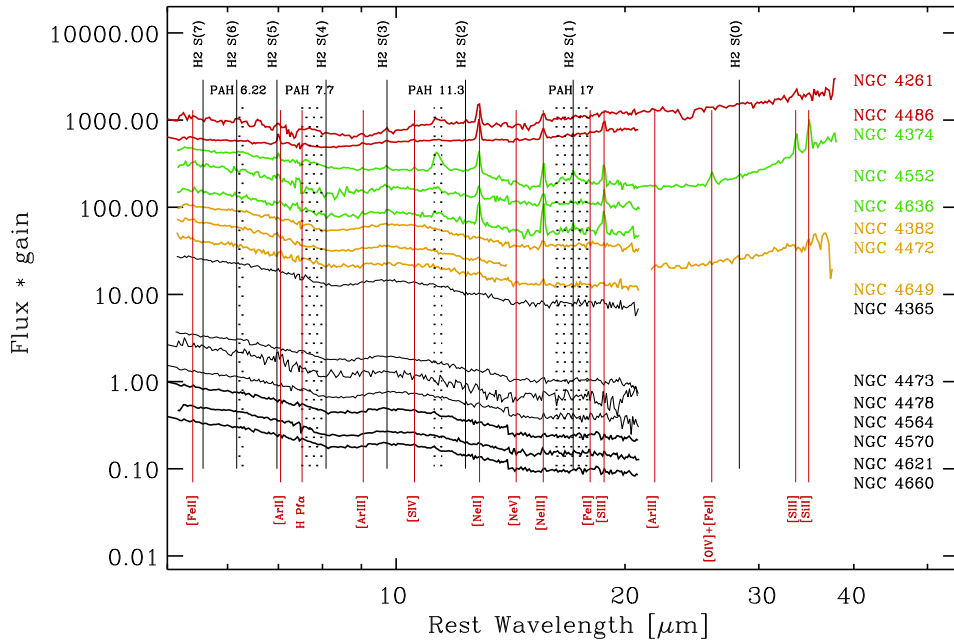


Fig. 1. ETGs in the sample of Kormendy et al. (2009). MIR classes are colour coded (black = class 0; yellow = class 1; green = class 2 and red = class 4). Nebular lines in the spectra are indicated with vertical red solid lines. PAH complexes are indicated with dotted areas. H₂ rotational emission lines are indicated with black solid lines.

in the sample show kinematical and/or morphological scars of recent accretion episodes.

In this note we investigate ETGs subdivided into the new, well defined photometric (*cuspy* vs. *core*) and kinematical (FR/SR) classes. To this end, we cross-correlate the MIR RSA sample described above with the Kormendy et al. (2009), Lauer (2012), Côté et al. (2006), Turner et al. (2012) and ATLAS^{3D} samples (see e.g. Emsellem et al. 2011, and references therein) to investigate the recent nuclear star formation history. 14 ETGs in Virgo, in particular the brighter ones, are in common with Kormendy et al. (2009) who classified them as either cuspy-core or core-less (i.e. *core* and *cuspy* in the present paper). 26 are in common with the ACSVCS+ACSFCS surveys in which galaxies are separated into core+Sersic and Sersic type nuclei (Côté et al. 2006; Turner et al. 2012). 41 out of 91 ETGs in the RSA MIR atlas are in common with the ATLAS^{3D} survey sample. For these galaxies Emsellem et al. (2011) provide a classification into FR or SR. The inner luminosity profiles of these ETGs have been classified into *cuspy* (power-law and intermediate) or *core* by Lauer (2012) (23 out of 41) and by Krajnović et al. (2013b) for a total of 44 objects.

3. MIR spectra vs. nuclear features in ETGs

3.1. The Virgo sample of Kormendy et al. (2009)

The structural and photometric properties of a sample of Es (some galaxies are classified S0 in the Revised Shapley Ames Catalogue (Sandage & Tammann 1987) as shown in Table 1) in the Virgo cluster have been well studied by Kormendy et al. (2009). The authors divided their sample according to departures, at small radii, from the Sersic, $\log I \propto r^{1/n}$, law. 10 Es with total absolute magnitudes $M_{VT} \leq -21.66$, i.e. the brightest objects of their sample, have *core* luminosity profiles. This class of ETGs *miss light* with respect to the extrapolation of the Sersic's law at small radii. 17 fainter galaxies, mostly Es in RSA, in the magnitude range $-21.54 \leq M_{VT} \leq -15.53$, are *cuspy*, having excess light in their centre with respect to the inward extrapolation of the outer Sersic profile.

With the exception of NGC 4406, all *core* ETGs in the Kormendy et al. (2009) sample, listed in the top part of Table 1, have a MIR spectrum in the RSA sample of Rampazzo et al. (2013). IRS spectra are also available for three *cuspy* ETGs, namely NGC 4621, NGC 4473 and NGC 4478. NGC 4570, NGC 4660 and NGC 4564, having absolute magnitudes similar to that of NGC 4478, also have IRS spectra but values for the extra light component have not been quantified by Kormendy et al. (2009). We collect the basic data in Table 1.

According to Kormendy et al. (2009), *core* and *cuspy* ETGs have fundamentally different properties. *Core* ETGs, are slowly rotating, have anisotropic velocity distributions, boxy isophotes, Sersic index $n > 4$ and are α -element enhanced, i.e. their stellar populations formed on short timescales. In contrast, *cuspy* ETGs rotate rapidly, are more isotropic and have disk isophotes. They tend to have lower values of the Sersic index, $n \simeq 3 \pm 1$, and be less α -enhanced. All *cuspy* ETGs are fast rotators, while the majority (7 out of 9) of *core* Es are slow rotators within $r_e/2$ (Emsellem et al. 2011) (Table 1, column 7).

The MIR spectra of the sub-set of Kormendy et al. (2009) ETGs is shown in Figure 1. All *cuspy* galaxies have a passive, class-0 spectrum characterized by the $10 \mu\text{m}$ silicon feature produced by oxygen rich AGB stars. Their kinematics show signatures of past interaction/accretion episodes, such as kinematically decoupled cores (KDC) and multiple velocity components

(MC). All have low nuclear X-ray luminosities ($38.18 \leq \log L_{X,nuc} \leq 38.92 \text{ erg s}^{-1}$, Pellegrini (2010)) indicating that no AGN are active, as also supported by the low radio power at 1.4 GHz (most are upper limits while NGC 4563 has $P_{1.4\text{GHz}} = 4.9 \times 10^{19} \text{ W Hz}^{-1}$, Brown et al. (2011)) (see also Rampazzo et al. 2013, Table B1).

A more active picture emerges for *core* ETGs. The MIR spectra indicate nuclei with different kinds of activity from AGN (class-4, M87 and NGC 4261) to post-star forming (MIR class-2 with anomalous PAHs, NGC 4374, NGC 4636, NGC 4552) to the quiescent nucleus of NGC 4365 (class-0).

Both SR, the majority, and FR show signatures of kinematical and morphological peculiarities suggesting the action of accretion episodes. Of particular interest is NGC 4382, which although showing strong shell features (see e.g. figure 9 in Kormendy et al. (2009)) has a nearly passively evolving nucleus (class-1). This is not the case for NGC 4374 and NGC 4552, that both show fine structure (see Sansom, Hibbard & Schweizer 2000), although less prominent than that in NGC 4382. The class-2 spectrum of NGC 4552 reveals the presence of gas and the additional presence of anomalous PAHs, as in NGC 4374, points to the occurrence of a recent star formation event.

Summarizing, there is evidence that accretions in brightest, *core* Es in the Kormendy et al. (2009) sample have triggered both AGN and SF activity, a challenge for completely dry mergers/accretions in the last few Gyrs. In contrast, the few *cuspy* galaxies in the present MIR sample are all passively evolving. They may have either be quiescent for a very long time (the radio power may take longer to vary (see e.g. Brown et al. 2011)) or possible accretions have been “sterile”, activating neither AGN nor star formation. An additional hint of a different recent evolution of the two photometric classes may come from the observation that dust appears to be totally absent in *cuspy* ETGs, while most of the *core* ETGs do show dust (col. 9 in Table 1). Clemens et al. (2010) found that dust can survive no longer than a few tens of Myr in the hostile ETG environment, so if present, should be quite recently acquired.

3.2. The ACS Virgo and Fornax ETGs samples

The passive evolution of all the 6 fainter, *cuspy* ETGs in our subset of the Kormendy et al. (2009) sample prompted us to enlarge the sample to fainter galaxies. A large HST study of the inner regions of ETGs in the Virgo and Fornax clusters has been performed by Côté et al. (2006) and Turner et al. (2012), the ACSVCS and ACSFCS respectively. The final sample with MIR spectra includes 23 ETGs in Virgo (top part of Table 2) and 8 ETGs in Fornax (bottom of Table 2) that have been classified by Turner et al. (2012) with an ACS class of either, *core* (originally non-nucleated) or *cuspy* (originally nucleated). Additional ETGs in low density environments, with a MIR spectrum in Rampazzo et al. (2013) and a Sersic decomposition of the luminosity profile, come from Krajnović et al. (2013b) and are reported in Table 2.

In Figure 2 we plot the absolute K_s -band magnitude distribution of *cuspy* and *core* ETGs in the Virgo and Fornax clusters (bottom left panel) and of the entire sample (bottom right panel). Côté et al. (2006) and Turner et al. (2012) noticed that virtually none of the bright ETGs are *cuspy*, in contrast to the fainter ones, as shown by the lower panel of Figure 2. The percentage of *cuspy* ETGs in Virgo and Fornax reaches $67\% \pm 8\%$ and $72\% \pm 13\%$ respectively among fainter galaxies in their sample. In the top left panel of Figure 2 we show the distribution of MIR classes in the same bins of M_K magnitude. Most of the *cuspy*

Table 2. The sample of ATLAS^{3D} ETGs with a *Spitzer*-IRS class

Ident.	Morpho. RSA	T	P	$\lambda_{re}/2$	$\epsilon_{re}/2$	$V/\sigma_{re}/2$	FR/SR _{$r_e/2$} class	n_{tot}	MIR class
NGC 821	E6	-4.8±0.4	cuspy	0.27	0.39	0.29	FR	10.4±0.7	0
NGC 2685	S0 ₃ (7) pec	-1.0±0.8	cuspy	0.63	0.19	0.73	FR	4.3±0.4	2
NGC 2974	E4	-4.2±1.2	cuspy	0.66	0.40	0.81	FR	4.0±0.4	2
NGC 3193	E2	-4.8±0.5	core	0.20	0.14	0.21	FR	5.3±0.1	0
NGC 3245	S0 ₁	-2.1±0.5	cuspy	0.59	0.44	0.58	FR	3.2±1.9	3
NGC 3377	E6	-4.8±0.4	cuspy	0.52	0.50	0.56	FR	5.0±0.5	0
NGC 3379	E0	-4.8±0.5	core	0.16	0.10	0.15	FR	5.3±0.9	0
NGC 3608	E1	-4.8±0.5	core	0.04	0.19	0.05	SR	3.9±0.5	0
NGC 4036	S0 ₃ (8)/Sa	-2.6±0.7	...	0.68	0.54	0.80	FR	2.0±0.1	2
NGC 4261	E3	-4.8±0.4	core	0.09	0.22	0.09	SR	5.1±0.4	4
NGC 4339	S0 _{1/2} (0)	-4.7±0.8	cuspy	0.31	0.06	0.30	FR	4.1±0.6	0
NGC 4365	E3	-4.8±0.5	core	0.09	0.25	0.11	SR	5.2±0.4	0
NGC 4371	SB0 _{2/3} (r)(3)	-1.3±0.6	cuspy	0.48	0.31	0.54	FR	3.8±0.6	2
NGC 4374	E1	-4.3±1.2	core	0.02	0.15	0.03	SR	6.0±0.3	2
NGC 4377	S0 ₁ (3)	-2.6±0.6	cuspy	0.34	0.23	0.31	FR	2.2±1.2	0
NGC 4382	S0 ₁ (3) pec	-1.3±0.6	core	0.16	0.20	0.17	FR	5.1±1.3	1
NGC 4435	SB0 ₁ (7)	-2.1±0.5	...	0.60	0.46	0.67	FR	4.7±0.3	3
NGC 4442	SB0 ₁ (6)	-1.9±0.4	cuspy	0.34	0.31	0.33	FR	2.8±0.2	0
NGC 4472	E1/S0 ₁ (1)	-4.8±0.5	core	0.08	0.17	0.07	SR	4.7±0.1	1
NGC 4473	E5	-4.7±0.7	core	0.25	0.40	0.26	FR	5.7±0.5	0
NGC 4474	S0 ₁ (8)	-2.0±0.5	cuspy	0.35	0.47	0.35	FR	3.5±0.4	2
NGC 4477	SB0 _{1/2} /SBa	-1.9±0.4	cuspy	0.22	0.13	0.21	FR	4.1±1.2	2
NGC 4478	E2	-4.8±0.4	core	0.18	0.17	0.17	FR	2.0±0.1	0
NGC 4486	E0	-4.3±0.6	core	0.02	0.04	0.02	SR	2.9±0.2	4
NGC 4550	E7/S0 ₁ (7)	-2.1±0.7	cuspy	0.06	0.63	0.07	SR	1.7±0.1	3
NGC 4552	S0 ₁ (0)	-4.6±0.9	core	0.05	0.05	0.05	SR	6.2±0.4	2
NGC 4564	E6	-4.8±0.5	cuspy	0.54	0.48	0.53	FR	2.9±0.2	0
NGC 4570	S0 ₁ (7)/E7	-2.0±0.7	cuspy	0.50	0.55	0.47	FR	2.4±0.2	0
NGC 4621	E5	-4.8±0.5	cuspy	0.29	0.36	0.27	FR	4.3±0.2	0
NGC 4636	E0/S0 ₁ (6)	-4.8±0.5	core	0.04	0.09	0.04	SR	5.5±0.5	2
NGC 4649	S0 ₁ (2)	-4.6±0.8	core	0.13	0.16	0.12	FR	5.1±0.5	1
NGC 4660	E5	-4.7±0.5	cuspy	0.47	0.32	0.52	FR	3.5±0.2	0
NGC 4697	E6	-4.4±0.8	cuspy	0.47	0.32	0.36	FR	4.6±0.2	3
NGC 5273	S0/a	-1.9±0.4	cuspy	0.48	0.12	0.51	FR	1.8±1.1	4
NGC 5353	S0 ₁ (7)/E7	-2.1±0.6	...	0.53	0.54	0.54	FR	3.3±0.5	2
NGC 5631	S0 ₃ (2)/Sa	-1.9±0.4	...	0.17	0.17	0.19	FR	4.3±0.5	2
NGC 5638	E1	-4.8±0.4	...	0.23	0.08	0.22	FR	3.5±0.2	0
NGC 5813	E1	-4.8±0.4	core	0.07	0.17	0.16	SR	5.8±1.7	1
NGC 5831	E4	-4.8±0.5	cuspy	0.06	0.20	0.16	SR	4.3±0.2	0
NGC 5846	S0 ₁ (0)	-4.7±0.7	core	0.03	0.06	0.04	SR	3.9±0.2	1
NGC 7332	S0 _{2/3}	-1.9±0.5	cuspy	0.34	0.44	0.29	FR	2.3±0.4	1
NGC 1339	E4	-4.3±0.5	cuspy	...	...	...	...	...	0
NGC 1351	S0 ₁ (6)/E6	-3.1±0.6	core	...	...	...	...	...	0
NGC 1374	E0	-4.4±1.1	core	...	...	...	...	...	0
NGC 1389	S0 ₁ (5)/SB0 ₁	-2.8±0.7	cuspy	...	...	...	...	...	0
NGC 1399	E1	-4.6±0.5	core	...	...	...	...	...	0
NGC 1404	E2	-4.8±0.5	core	...	...	...	...	...	1
NGC 1427	E5	-4.0±0.9	core	...	...	...	...	...	0
IC 2006	E1	-4.2±0.9	cuspy	...	...	...	...	...	1

ETGs in ATLAS^{3D} (top part of the table), including the Virgo sample, plus Fornax cluster ETGs (Turner et al. 2012) represent the global sample used for the *core* vs. *cuspy* and FR vs. SR analyses. Morphological classifications in columns 2 and 3 are from RSA and LEDA, respectively. For the ATLAS^{3D} sample, the profile type (column 4), P, is *cuspy* (originally \backslash =power law, \wedge = intermediate) and *core* (originally \cap) is taken from Krajnović et al. (2013b). The specific angular momentum (column 5), $\lambda_{re}/2$, the ellipticity (column 6), $\epsilon_{re}/2$, the rotation velocity to velocity dispersion ratio (column 7), $V/\sigma_{re}/2$ and the kinematical class (column 8), FR/SR, at $r_e/2$ are from Emsellem et al. (2011). The Sersic index (column 9), n_{tot} , is from Krajnović et al. (2013a). The MIR class (column 10) is taken from Rampazzo et al. (2013).

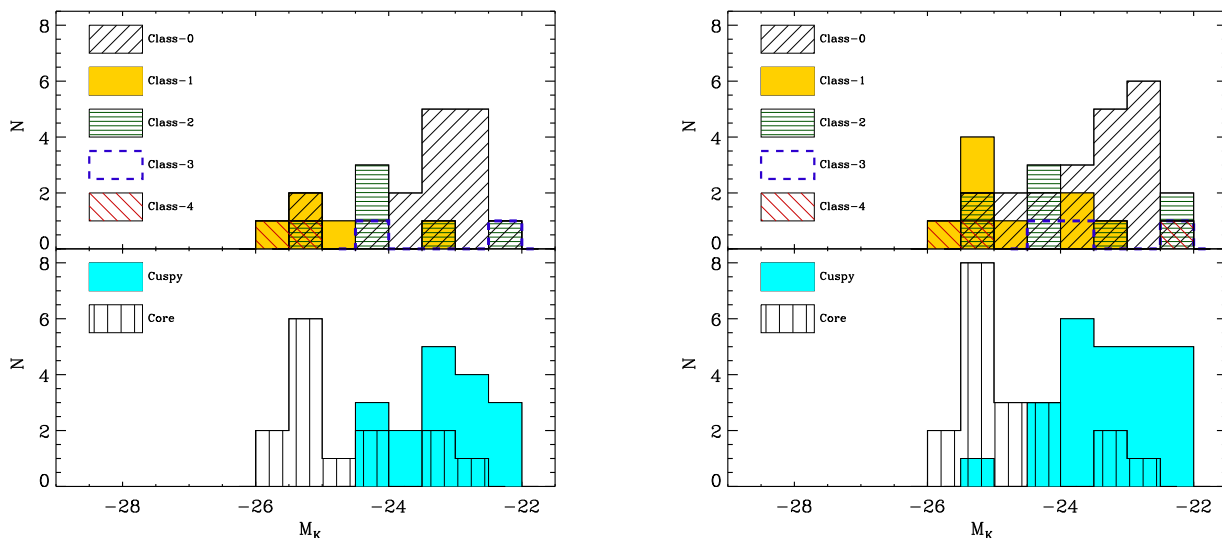


Fig. 2. K_s -band absolute magnitude, M_K , distribution vs. MIR classes (top panels) and *cuspy/core* ETGs in the Virgo plus Fornax clusters (Côté et al. 2006; Turner et al. 2012) (left panel) and in the total sample, including ETGs in low density environments in Krajnović et al. (2013b).

ETGs have MIR class-0 spectra, indicating passive evolution in their nucleus. Considering ETGs with $M_K \geq -24$, $82^{+18}_{-16}\%$ of the galaxies are *cuspy*, of which $59^{+25}_{-18}\%$ are passively evolving and only $18^{+17}_{-10}\%$ show PAH features. The brightest ($M_K \leq -25$) ETGs have *cores*, and various MIR spectra are found, from class-0 to class-4, as noticed before in the Kormendy et al. (2009) sample. However, active MIR classes, from 1 to 4, are distributed along all the M_K range examined, suggesting that “wet” accretions occur at all magnitude/mass bins.

In the right panels of Figure 2 we consider the entire sample of 44 ETGs with a MIR spectrum and a *core/cuspy* classification. Of the whole sample, $62^{+22}_{-15}\%$ of the passive ETGs are *cuspy*. For the subset fainter than $M_K = -24$, $87^{+23}_{-18}\%$ are *cuspy*, $57^{+22}_{-16}\%$ are passively evolving and $33^{+18}_{-12}\%$ show PAHs in their MIR spectra. Although the increase in number of galaxies is modest going from cluster to low density environments, the number of active galaxies (classes 1, 2, 3 and 4) tends to increase at all magnitude/mass bins, suggesting a possible environmental effect (see e.g. Clemens et al. 2006, 2009). E.g. Serra et al. (2012) detected HI in 40% of ETGs outside Virgo and 10% inside it.

4. MIR spectra vs. fast and slow rotators

With the aim of investigating the MIR properties of FRs vs. SRs in the $r_e/2$ region, we cross-correlate the samples adding a measure of the specific angular momentum to our sample with a MIR nuclear classification. 41 out of 91 ETGs in the Rampazzo et al. (2013, Table 5) sample of MIR spectra have a measure of the specific angular momentum. Table 2 provides the list of ETGs with a FR/SR classification within $r_e/2$ (column 8 from Emsellem et al. (2011, ATLAS^{3D}: Table B1)) and their MIR class (column 10). The list includes 29 FRs and 12 SRs. The Fornax ETGs lack the kinematical classification in the $r_e/2$ region.

In Figure 3 the specific angular momentum at $r_e/2$, $\lambda_{r_e/2}$, is plotted against the corresponding average ellipticity, $\epsilon_{r_e/2}$, (Table 3.1, columns 5 and 6). According to Lauer (2012) the dashed line in the figure separates the *core* and *cuspy* ETGs into different

rotation classes, leaving the *core* set contaminated only by face-on *cuspy* galaxies. The figure shows the 23 galaxies of Lauer (2012), among the 41 ETGs in Emsellem et al. (2011) (large squares for SR, large circles for FR). Figure 3 plainly shows that different MIR classes are found associated with both FR and SR, as well as in *core* and *cuspy* ETGs.

$25^{+24}_{-14}\%$ of SRs and $52^{+17}_{-13}\%$ of FRs have a class-0 spectrum i.e. are passively evolving. On the other hand, of those MIR classes showing emission lines (1, 2, 3 and 4), i.e. the complement of passive ETGs, $75^{+25}_{-24}\%$ of SRs and $48^{+17}_{-12}\%$ of FRs are gas rich in their nucleus. In the whole sample of Rampazzo et al. (2013), $64^{+12}_{-6}\%$ of the nuclei show emission lines, although with different intensity. This results are in agreement with optical studies, in which, depending on the sample the ionized gas is detected in ≈ 50 -90% of ETGs (Phillips et al. 1986; Macchetto et al. 1996; Sarzi et al. 2006, 2010; Yan et al. 2006; Serra et al. 2008; Annibali et al. 2010). This suggests that *wet-mergers/accretions* play a role in the recent few Gyrs history of both SR and FR.

$50^{+30}_{-20}\%$ of SRs and $38^{+15}_{-11}\%$ of FRs show PAH features (MIR classes 2, 3, 4), indicating that in about half of both SR and FR a star formation episode has recently occurred (Kaneda et al. 2008; Panuzzo et al. 2011; Rampazzo et al. 2013). Galaxies with normal PAH ratios, class-3 spectra, are a minority: only $10^{+8}_{-5}\%$ of FR show star forming spectra and $8^{+19}_{-2}\%$ SR. All MIR class-4 spectra, $17^{+22}_{-11}\%$ of SR and $3^{+8}_{-1}\%$ of FRs, show PAHs. The optical study of 65 ETGs of Annibali et al. (2010) provided indications that the AGN phenomenon is associated with star formation.

5. Summary and Conclusions

This note investigates whether the photometric segregation between *cuspy* and *core* nuclei and/or the dynamical segregation between fast and slow rotators can be attributed to formation via “wet” or “dry” mergers.

We explore the question by comparing the MIR spectral characteristics with their *cuspy/core* morphology (Kormendy et al. 2009; Lauer 2012; Côté et al. 2006; Turner et al. 2012; Krajnović et al. 2013a) and FR/SR characterization (ATLAS^{3D}). We use *Spitzer*-IRS spectra and MIR classes discussed in Panuzzo et al. (2011) and Rampazzo et al. (2013).

¹ The fractions reported consider upper and lower errors corresponding to 1σ Gaussian errors (Gehrels 1986).

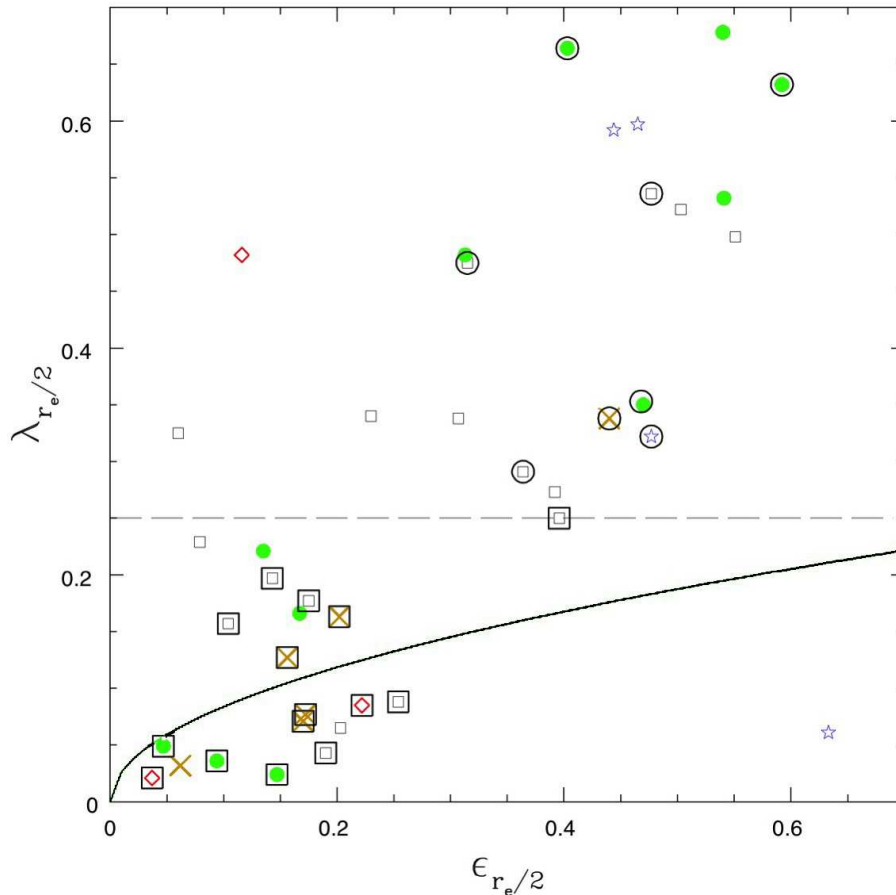


Fig. 3. Specific baryonic angular momentum, $\lambda_{re/2}$, vs. average ellipticity, $\epsilon_{re/2}$, measured for the 41 ETGs in Table 2 (see references in the table caption.) The solid line separates FR from SR according to Emsellem et al. (2011). The dashed line separates ETGs with *cuspy* profiles (large circles) from *core* galaxies (large squares) in the sample of Lauer (2012). MIR classes are coded as follows: square = class 0; cross = class 1; full dot = class 2; star = class-3 and diamonds = class 4.

These spectra are sensitive to the recent few Gyr ($z \lesssim 0.2$) evolution of the ETGs. We find the following:

- With the exception of NGC 4365, which is passively evolving, MIR spectra of all the bright *core* ETGs in the Kormendy et al. (2009) sample show nebular emission lines, and PAH features are detected in 5 out of 9 objects. These types of nuclei should have recently accreted gas-rich material. If such objects formed via “dry” mergers, the process was completed before $z \sim 0.2$ and “wet” accretions have happened since. AGN feedback does not prevent a late star formation episode in the bright Es NGC 4374, NGC 4636 and NGC 4552. The few (6) faint, *cuspy* ETGs in the Kormendy et al. (2009) sample all show passively evolving spectra, irrespective of their magnitude.
- MIR spectra of the total *cuspy/core* sample (44 ETGs), confirm that ETGs fainter than $M_K = -24$ mag, mostly *cuspy*, are predominantly passively evolving. This fact is particularly significant in Virgo and Fornax where $82^{+18}_{-10}\%$ are *cuspy*, the majority also FRs. Kormendy et al. (2009) noticed that *cuspy* ETGs have disky (positive a_4/a Fourier coefficient) isophotes in the nuclear region, a structure that suggests some form of dissipation during the formation. The passive MIR spectra suggest that either this infall was sterile, i.e. without star formation, or happened at $z \gtrsim 0.2$, so as to leave no trace in the present MIR spectra. Khochfar et al. (2011)

models suggest that a fraction of FR lying in high-density environments have a residual gas fraction below 15%, i.e. they have exhausted their cold gas reservoir and have no hot halo from which gas can cool. Counterparts in low density environments (Figure 2 right panel) show the tendency to be more gas rich and hence more active.

- A significant fraction of both FR ($38^{+18}_{-11}\%$) and SR ($50^{+34}_{-21}\%$) shows PAH features in their MIR spectra. Ionized and molecular gas are also commonly detected. Recent star formation episodes are not a rare phenomenon in either FR or SR, even in those dominated by AGN activity (see also. Annibali et al. 2010). Recently, observing HI rich ETGs, Serra et al. (2014) found that SRs are detected as often, host as much H I and have a similar rate of H I discs/rings as FRs.

Despite the expectation that the signature of “wet” or “dry” merger is strongest in the galaxy nucleus, the nuclear MIR spectra do not clearly link the *core* versus *cuspy* morphology and the FR versus SR kinematical class to these alternative formation scenarios. Within the last few Gyrs, only at the two extremes of the ETG luminosity, does the dichotomy emerge: the brightest *core*, mostly SR and faint *cuspy*, mostly FR (in the Virgo and Fornax clusters) separate into mostly active and passive ETGs, respectively. The result, however, is in contrast to what is expected for *core*-SR versus *cuspy*-FR, i.e. a “dry” versus “wet” accretion scenarios.

The obvious possibility is that these photometric and kinematical classes are signatures generated by the two different evolutionary scenarios at $z \gtrsim 0.2$ (see e.g. Khochfar et al. 2011), so that they do not affect the MIR spectra. On the other hand, adopting the traditional E/S0s morphological subdivision Rampazzo et al. (2013) found that Es are significantly more passive than S0s in the same epoch. FR/SR classes may smooth away differences between Es and S0s, since a large fraction of Es transit into the FR class. At the same time, recent observations tend to emphasize the complexity of ETGs when their study is extended to large radii (see also Serra et al. 2014). Arnold et al. (2014) recently obtained the extended, up to $2-4 r_e$, kinematics of 22 ETGs in RSA. They find that only SRs remain slowly rotating in their halos, while the specific angular momentum of ETGs classified as FR within $r_e = 1$, may dramatically change at larger radii. Arnold et al. (2014) suggest that the traditional E/S0 classification better accounts for the observed kinematics up to large radii and likely of their complex evolutionary scenario.

Acknowledgements

RR acknowledges partial financial support by contracts ASI-INAF I/016/07/0 and ASI-INAF I/009/10/0. OV acknowledges support from the Conacyt grant CB-2012-183013. This research has made use of the NASA/ IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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